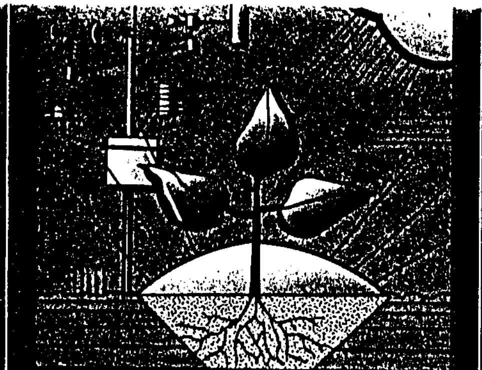

EVAPOTRANSPIRATION AND IRRIGATION SCHEDULING

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Sources of Biased Errors in Evaluating Evapotranspiration Equations [1/]

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ABSTRACT

The accurate estimation of water use by crops is critical in water resource planning. To do this, accurate estimates of maximum, energy limited evapotranspiration rate for a specific crop (ET_x) are a prerequisite so that differences in weather conditions between locations and seasons can be accounted for. Developing broadly applicable daily ET_x equations requires accurate measurements of ET_x and accompanying weather data. This paper reports on probable errors found in both these sets of measurements in available data sources from a diversity of locations. The primary biased errors were associated with apparent improper calibration of solar radiometers and with defining the effective area of a lysimeter. Solar radiation data from Davis, California, where lysimeter data are abundant, had biases that averaged 6% high for nine years. One year had little bias and others had up to 10% high biases. Another major source of lysimeter data is Coshocton, Ohio, where solar radiation biases of 17% low were found for the three years studied. The effective area of the Coshocton lysimeters may need adjustments by as much as 20% to compensate for rim errors and exposure errors. Carefully managed lysimeters were found to have up to ±10% biases that were probably caused by overlapping of vegetation from the lysimeter area with the surrounding area. Results from this study indicate that caution should be used when interpreting data from lysimeter sources for developing and calibrating ET_x equations because of these possible biases.

KEYWORDS: alfalfa, lysimeters, solar radiation, vapor pressure deficit, wind, wheat

INTRODUCTION

Verifying energy limited or maximum evapotranspiration (ET_x) estimation equations for specific vegetation types requires accurate measured ET_x and associated weather and crop data. All experimental data contain some inaccuracy owing to instrument errors, observation errors and instrument exposure errors. If errors in experimental measurements are random and small, estimation equations for evapotranspiration should be reasonably consistent between sites and for seasons. If, however, the errors are systematically biased the equations or coefficients resulting from the analysis will likely be biased. A biased error is defined as a systematic error occurring continuously in the measurements. An example is a temperature record indicating a value higher than the actual temperature along with the usual random measurement errors.

In the course of evaluating a daily (24 hr) maximum evapotranspiration (ET_x) equation for universality of application, several weighing lysimeter measurements ET_x and the required weather data sets were obtained from locations with contrasting climate and crops. The

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principal bias of concern was the lysimeter effective area used to convert the mass change to depth of water. The effective area is not the actual area of the lysimeter soil surface as pointed out by Makkink (1959), King et al. (1956), and Tanner (1967). The area of the rim space between the soil inside the lysimeter and the soil outside the lysimeter retaining wall is accounted for in some reports (Wright, 1988; Meyer et al., 1987) while not being mentioned in other reports. This area may be 5 to 15% of the lysimeter soil surface area. When plants grow in and around the lysimeter, the leaves will overlap the rim space, using the additional energy from that space in the evaporation process. Makkink (1959) suggested that discontinuities of vegetation in and around a lysimeter can be significant sources of systematic errors. Small lysimeters with large borders are vulnerable to having plants that are different from surrounding field plots in the same soil. This is especially true if the outside of a lysimeter is partially bare and the inside is well vegetated. Lysimeters such as those at Coshocton, Ohio (Harrold and Dreibelbis, 1958) had 20 cm thick gaps between the inner wall and outer retaining wall. The near-surface gap area was later reduced to 7.6 cm (Harrold, 1966).

Another possible source of error is the measured solar radiation data. These data are of primary importance in calculating net radiation in ET_x equations. If solar radiometers are not properly calibrated and maintained, biased results are possible. All pyranometers have the problem of the position of the sun relative to the position of the instrument, especially at zenith angles > 60°. Another problem that has affected historical solar radiation data is the change in response characteristics of the instrument with age or exposure to solar radiation. According to Flowers and Starke (1967) some of the pyranometers used from the early 1950's through 1975 were subject to reductions in sensitivity due to changes in the color of the paint used to coat the absorbing surfaces. These color changes resulted in decreases in sensitivity as great as 15%. The major network of solar radiation measurements operated by the U.S. Dept of Commerce until about 1970 was discontinued partly because the historical record of solar radiation could have errors exceeding 10% as a result of these factors.

It is probable that most agricultural technicians and scientists involved in measuring solar radiation do not have the same intuitive knowledge about accuracy of solar radiation measurements as they have about air temperature and rainfall data because the latter two are a part of everyday conversation. Thus, errors in radiation measurements can go undetected for long times with bias. Once biased errors are detected and eliminated, there still remains the need for correction, if possible, of the previous data.

This paper identifies the probable biased errors in some lysimeter evaporation data and the weather data used by various researchers to calibrate or test ET_x equations. Data used came directly from our research measurements or from ASCE Manual No. 70 of the American Society of Civil Engineers (Jensen et al., 1990), hereafter referred to as ASCE 70. The analysis was done for three years of wheat grown at Bushland, Texas (USA), and Griffith, NSW (Australia); for three years of alfalfa grown at Kimberly, Idaho (USA); and for three years of grass-legume mixture grown at Coshocton, Ohio (USA); and for three years of fescue grass grown at Davis, California (USA).

METHODOLOGY

The desired method for evaluating lysimeter effective area is to compare lysimeter results with a common maximum evapotranspiration (ET_x) equation evaluated using weather data from each lysimeter site. The lysimeter data were required to be from two or more years at the same location and for the same crop, from two lysimeters in the same year at the same site and for the same crop, or for the same crop at different locations. Using the same crop ensured that there would be no bias introduced in the event of differences in crop stomatal conductance between species.

To test weather related biases, data from a research site was compared with other available sources in the region. An effective method of evaluating evapotranspiration biases was to graphically display the sum of differences between ET_x equation estimates and measured evapotranspiration when conditions of the lysimeter were favorable for ET_x. Favorable

conditions include an almost complete crop cover and no soil water deficit. Using two or more sets of data for the same crop, a common ET_x equation was adjusted with an empirical constant in the aerodynamic term of a combination equation such that the sum of the difference between the first and last day of data was equal to zero. Biases became obvious if the sum of the differences were predominantly straying from zero in the same direction for a particular site or lysimeter. The same procedure was used to compare solar radiation and air temperature measurements between sites. Assuming that the experimental site should be equal, on average, to a nearby site, differences in radiation between the comparison site and the experimental site were summed and graphed from a spreadsheet. Biases between locations become evident if time trends in the sum of differences change in unusual patterns. Radiation biases were also analyzed by regression of the lysimeter site data with a nearby weather station that had quality assessed radiation data available.

EVALUATION SITES AND CROPS

Data from the junior authors of this paper were made available to the senior author for locations in Bushland, Texas (Howell) and Griffith, NSW, Australia (Meyer) for multiple years of wheat ET_x and weather measurements. The Bushland wheat experiment and data are for the years 1988-93 and have been reported by Howell et al. (1995). The Griffith data were reported by Meyer et al. (1987) and were measured in 1984, 1986, and 1987. Weather and ET_x data for alfalfa grown at Kimberly, Idaho were available from ASCE 70. Kimberly data cover the parts of the growing season when ET_x conditions existed during the years of 1969, 1970 and 1971 and are reported in Wright (1988). Fescue grass data from Davis, California and the grass-legume mixture from Coshocton, Ohio, along with the concomitant weather data also were obtained from ASCE 70. Digitized data from ASCE 70 were kindly provided by ASCE 70 co-editor R.G. Allen. Davis data were selected for 1964-1966 for evapotranspiration evaluation and for 1964-1972 for solar evaluation; Coshocton data were for 1977-1979.

The combination ET_x equation was defined as follows:

$$ET_x = \frac{[\Delta(R_n - G) + (\gamma E_a)]/\lambda}{\Delta + \gamma} \qquad (1)$$

where ET_x is in mm d^{-1}, Δ is the slope of the saturated vapor pressure-temperature curve in kPa/°C, R_n is net radiation in MJ m^{-2} d^{-1}, G is soil heat flux in MJ m^{-2} d^{-1}, λ is the latent heat of vaporization in MJ kg^{-1}, γ is the psychrometer constant in kPa/°C, E_a is the 'evaporating power of the air' in MJ m^{-2} d^{-1}. E_a is defined as

$$E_a = f(u)\ VPD \qquad (2)$$

where f(u) is the wind function in MJ m^{-2} d^{-1} kPa^{-1} and VPD is vapor pressure deficit in kPa. With u (2 m wind speed in m s^{-1}), $f(u)$ is often defined as a linear function. For alfalfa, a linear wind function (Eq. 6.15C in Jensen et al., 1990) was used and is given as

$$E_a = 6.43\ (1.0 + C_w\ u)\ VPD \qquad (3)$$

where C_w is the wind speed factor in s m^{-1}. For all crops a function similar to Eq. 3 without wind was evaluated from the lysimeter weather data used in this paper and is given as

$$E_a = C_v \, VPD \tag{4}$$

where C_v is a vapor pressure deficit coefficient in MJ m^{-2}day^{-1}kPa^{-1}. The potential lysimeter gap (or edge) bias factor C_b is defined as

$$C_b = \frac{ET_x}{ET_m} \tag{5}$$

where ET_m is the lysimeter evapotranspiration in mm d^{-1}.

RESULTS AND DISCUSSIONS

Solar Radiation

The Davis and Coshocton solar data had relatively large year to year variations in clear day solar radiation that should be rather consistent between years. To check the consistency and accuracy of the Davis and other U.S.A. data sources, daily solar radiation data were aggregated from hourly values for the nearest site from the recently available National Solar Radiation Data (NSRDB, 1992). The data are available for 239 sites from 1961-1990[3/]. The data for each site are from quality assessed measurements or from modeled values that account for clouds and other meteorological information. Sacramento, CA is the nearest site to Davis, being about 25 km away. The Sacramento data had little year-to year variation in clear days for various parts of the year. Assuming the quality assessed Sacramento data are correct, the bias for Davis was evaluated by calculating the daily differences between Davis and Sacramento. Differences were accumulated on an annual basis (Fig. 1). Solar data for Davis started on 1 May 1964 and ended on 1 May 1972. Except for parts of 1964 and 1969, and all of 1965, cumulative differences were large, indicating a high bias for Davis if Sacramento values were correct. The average for Davis was 19.25 MJ m^{-2} d^{-1}. The average for Sacramento was 17.74 MJ m^{-2} d^{-1} (Table 1). There were several periods when the slope of the annual cumulative difference curve was relatively constant. A multiplier of approximately 0.88 for Davis data reduced those slopes to near zero. When that was done however, there were still apparent biases for different periods. For more consistency in radiation data it was concluded that the Davis data should be replaced with the Sacramento data for best accuracy in evaluation of ET_x equations.

The NSRDB source was sufficiently dense so that all U.S. locations had stations within 150 km or less of the stations where lysimeter data were available to check the apparent quality of the lysimeter locations solar radiation data. A regression was done between the solar data available for each day of lysimeter measurements and from the NSRDB source. The regression was done with the NSRDB values as the independent variable and the lysimeter location values as the dependent variable. The intercept was forced through the origin. The results (Table 1) demonstrate that the Davis and Coshocton data have quite large differences between the neighboring locations while the Bushland and Kimberly data matched the neighboring stations of

[3/] The NSRDB is available through the National Climatic Data Center, User Services, Asheville, NC.

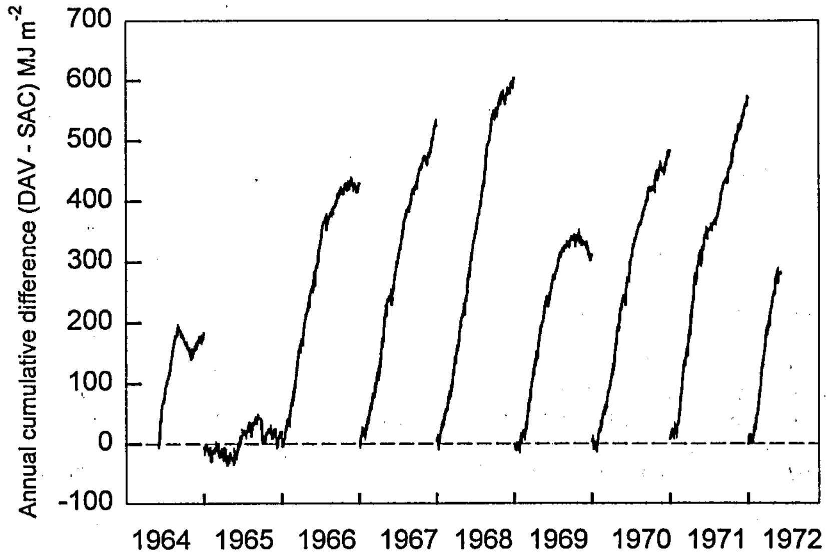

Figure 1. The annual cumulative differences in daily solar radiation data between Davis, CA and Sacramento, CA for a sequence of days between June 1964 and May 1972.

Table 1. Statistical comparisons of solar radiation data from locations where lysimeter (LYS) evapotranspiration measurements were made and stations in its vicinity from the National Radiation Data Base (NSRDB). BUS = Bushland, TX; AMA = Amarillo, TX; DAV = Davis, CA; SAC = Sacramento, CA; COS = Coshocton, OH; COL = Columbus, OH; KIM = Kimberly, ID; BOI = Boise, ID.

SOLAR COMPARISON FOR LYSIMETER AND WEATHER SITES							
Locations	Years	LYS mean MJ m^{-2}d^{-1}	NSRDB mean MJ m^{-2}d^{-1}	Slope	RMSE MJ m^{-2}d^{-1}	R^2	N
BUS-AMA	89-93	23.42	23.36	0.994	2.31	0.82	765
DAV-SAC	64-72	19.25	17.74	1.060	4.41	0.77	2708
COS-COL	77-79	10.03	13.89	0.750	3.07	0.82	1095
KIM-BOI	69-71	23.26	23.33	1.003	3.02	0.72	370

Amarillo, TX and Boise, ID quite well with the slope being almost 1.00. The Coshocton data were 3.86 MJ m^{-2} d^{-1} too low on average. Many of the cloudy day radiation values were much lower than those recorded for any station in similar latitudes. For analysis of an ET_x equation from Coshocton, the solar radiation data were replaced with those from Columbus. Although there was not a comparison standard for Griffith, the atmospheric transmissivities for clear days were consistent between years and averaged about the same as clear day transmissivities at Kimberly and Bushland. Therefore, the Griffith data were considered to have no apparent biases, as were the Kimberly and Bushland solar radiation data.

Evapotranspiration

The Kimberly alfalfa data contained 10 growth cycles over three years. A wind function for a combination equation was fit by choosing a value that minimized the errors between the estimated and measured data. The C_a value of 0.98 s m^{-1} resulted in zero cumulative difference between estimated and measured evapotranspiration values, using all three years data. The cumulative daily errors for each year are shown in Fig. 2A. The 12-16 day gap in data points in Fig. 2 for each year represents times after cutting before a full cover was re-established. The results revealed that the use of a single constant in the wind function causes systematic errors for different parts of the year. Errors were mostly all positive before DOY 140 and after DOY 260. Between those dates, the errors were mostly negative. For best accuracy, one would need to fit a wind function for each of those periods as done by Wright (1982). When a fitted constant is used (C_v, Eq. 4) instead of the wind function, the error trend is smaller (Fig. 2B). The C_v value for these data was 22.5. Cumulative errors for a single cutting were primarily unidirectional in three cases, cutting 4 in 69, and cutting 1 and 3 in 1971. Assuming these errors were associated with the overlapping of vegetation over the gap, a lysimeter correction factor (C_b) was determined that minimized the error trend. The correction factors needed for each of the cases were 1.07 for the last cutting in 69 and 0.92 for the first and last cutting of 1971. Lysimeter correction values below 1 indicate that, on average, leaves lap over from the outside to the inside of the lysimeter, and vice versa for values greater than 1. Cumulative errors after lysimeter corrections were considerably smaller (Fig. 2C). Further information about the alfalfa analysis is provided in Table 2.

Table 2. Vapor pressure deficit coefficients (C_v) for the combination equation fitted for various crops and locations before (ongoing) and after (corrected) biases are considered. RMSE is the root mean square error. BU = Bushland, TX; GR = Griffith, AU; DA = Davis, CA. The alfalfa wind case is a wind speed coefficient (C_a).

CROP		C_v	RMSE mm d^{-1}
Wheat	BU Original	26.0	1.17
	BU Corrected	27.1	1.15
	GR Original	27.3	0.85
	GR Corrected	27.3	0.83
	All Corrected	27.3	0.99
Alfalfa	Wind	0.98(C_a)	0.93
	Original	22.5	0.99
	Corrected	22.2	0.96
Grass	DA Original	13.7	0.99
	DA Corrected	16.5	0.83
	CO Original	8.6	1.00
	CO Corrected	16.5	1.64

The wheat ET_x from Bushland and Griffith had trends in cumulative errors similar to the alfalfa data. Therefore, only the VPD multiplier (C_v) was used to determine trends in possible errors. Values of C_v of 26.0 and 27.1 for Bushland and Griffith, respectively, minimized the errors. Trends in the error are depicted in Figure 3A. Unidirectional trend existed for Bushland in 1988 and for Griffith in 1987. Lysimeter correction factors (C_b) of 1.1 for Bushland 88 and 1.05 for Griffith 87, along with a change in C_v to 27.3 provided minimum errors (Fig. 3B, Table 2).

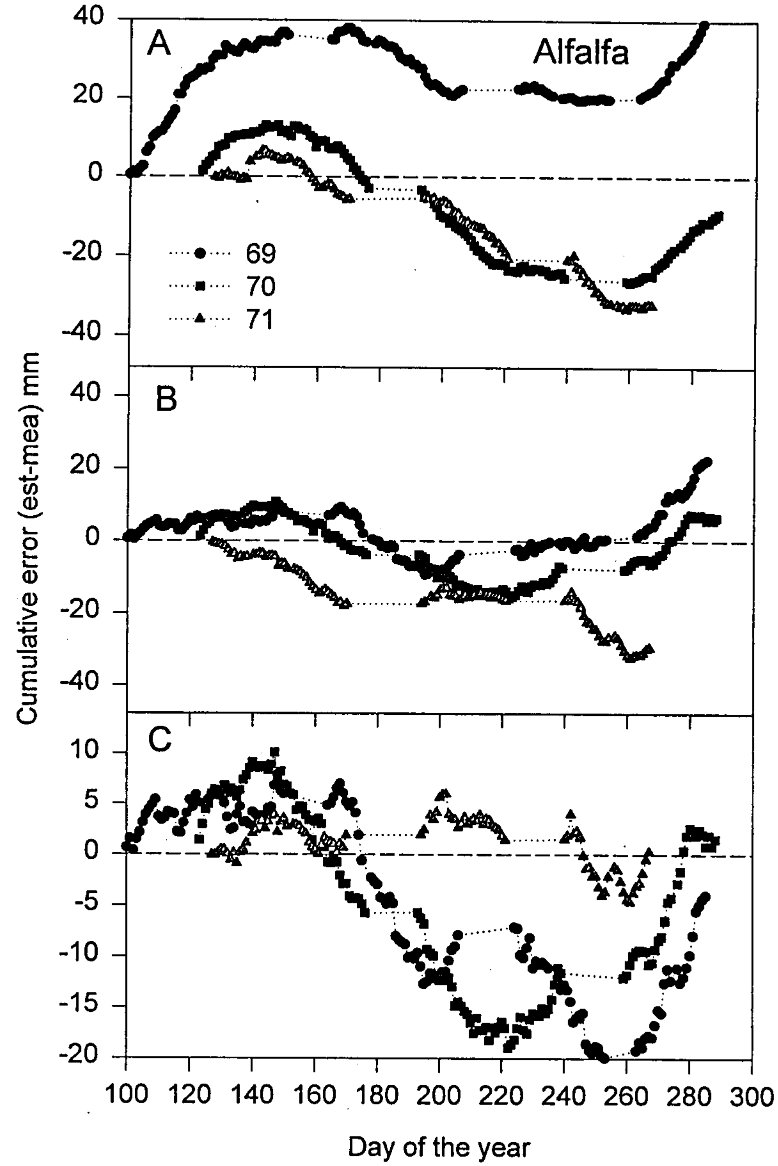

Figure 2. Cumulative annual differences of daily values of estimated minus measured evapotranspiration for alfalfa at Kimberly, ID. 2A is for a fitted wind function for a Penman equation; 2B used a combination equation without wind and fitted multiplier for the vapor pressure deficit (VPD); 2C same as 2B with lysimeter biases corrected.

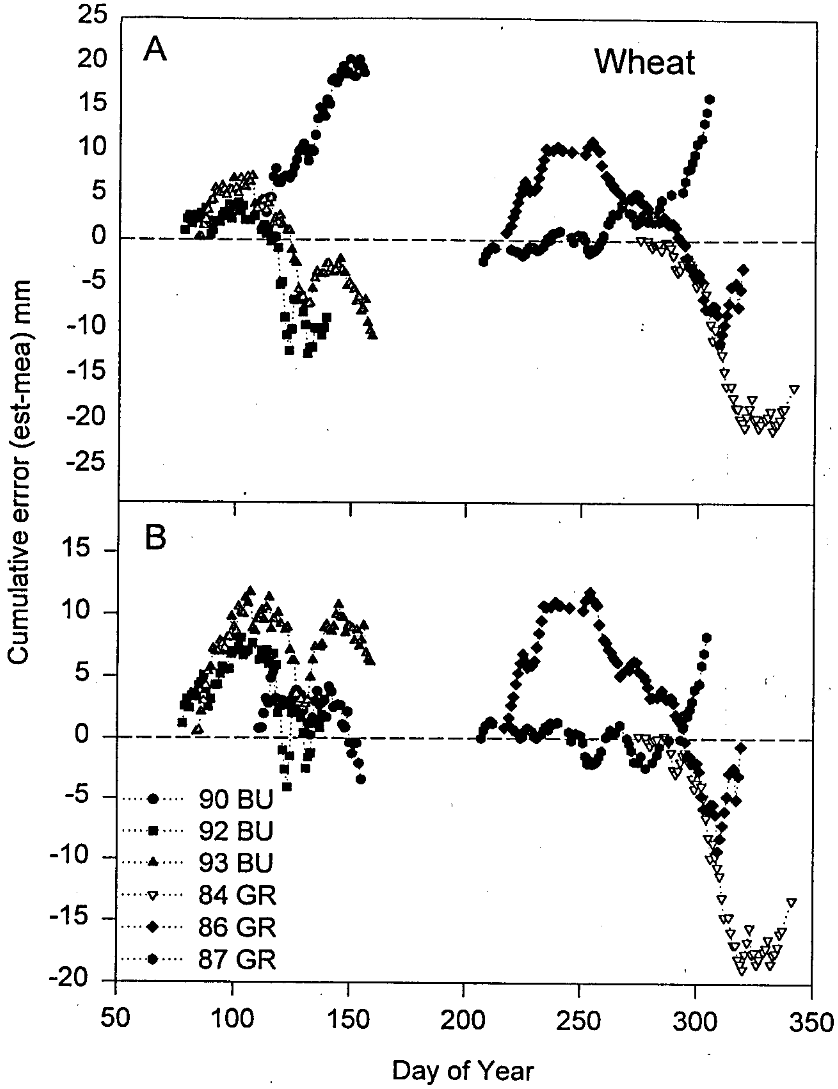

Figure 3. Cumulative annual differences between daily estimated minus measured evapotranspiration for wheat at Bushland (BU), TX and Griffith (GR), NSW; 3A uses a fitted vapor pressure deficit (VPD) constant to minimize the errors for all data at each location; 3B uses a common constant multiplier of the VPD for both locations with a lysimeter correction for BU90 and GR87.

The Davis grass ET_x evaluation for 1964 to 1966, using the Sacramento solar data and eliminating the days with rainfall, required a C_v of value 13.7 to minimize the errors. The 1966 data contained trends that were different in direction from the other two years, indicating a possible bias in the lysimeter measurements or a difference in the vegetation. When a lysimeter correction constant (C_b) of 1.12 was used for 1966, the trends in cumulative errors were similar for each year (Fig. 4). With that adjustment in the evapotranspiration measured values, 16.5 was the most appropriate C_v value for minimal trends in errors for the first two thirds of the warmer season at Davis. Since all years trended upward for the latter third of the season, there may be a problem with the concept of Eq. 4 or the vegetation was not using water at the maximum rate.

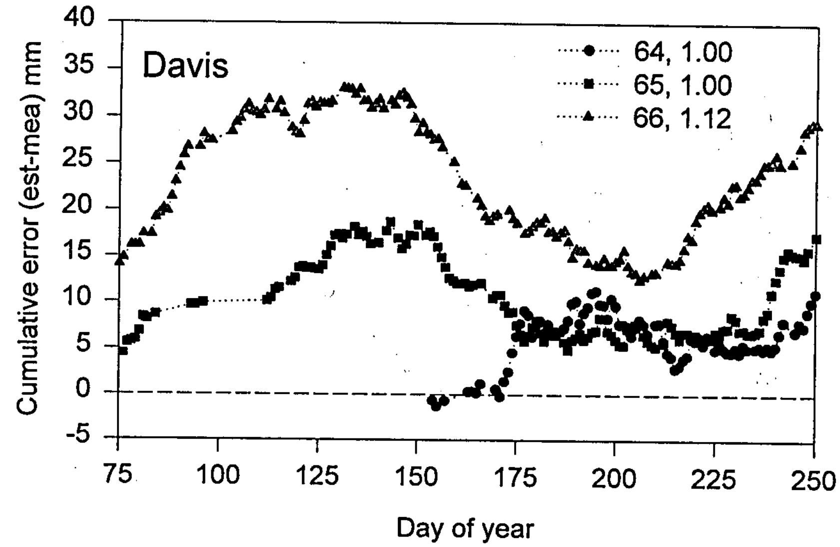

Figure 4. Cumulative annual differences between daily estimated minus measured evapotranspiration for grass at Davis (DA), CA with a lysimeter correction for 1966 using a fitted vapor pressure deficit (VPD) constant for 6.7 in a combination equation to minimize the errors.

The Coshocton data were the most difficult to evaluate. The solar data from the site were biased and were replaced by data from Columbus for the study. Furthermore, several problems with errors in the lysimeters, as discussed by Harrold and Dreibelbis (1977), must have existed. The errors of concern were associated with condensation on the lysimeter walls and inaccuracy of the weighing system. One of the main problems of evaluating the data for use in comparison with other sites is that the lysimeter used in this study is on a 23% slope with an east-southeast aspect. The lysimeter surface area used for conversion of mass change to water depth was the projected horizontal area of the inside of the lysimeter. Problems associated with the solar data, the soil slope, and the effective lysimeter area probably indicates that no further analysis should be done because of these large uncertainties. However, because the data taken from the lysimeters at Coshocton are potentially available for over 50 years and are still being taken to date, some idea of the possible conversion of measured data to equivalent horizontal evapotranspiration could be valuable for evaluating ET_x equations. Assuming the evapotranspiration values are correct, a C_v value of 8.6 minimized errors. This low multiplier, being almost half that found most appropriate for Davis, may indicate that a constant lysimeter calibration factor for Coshocton would be needed to provide similar values to Davis since the vegetation type was quite similar. The C_b value found to be appropriate to obtain a C_v value of 16.5 was 1.27 for 77 and 78 and 1.15 for 79. Trends in cumulative errors, using the C_b and C_v values for the warmer part of the season are depicted in Fig. 5. The RMSE for these approximated values was 1.64 mmd^{-1} and the value for the original data was 1.0 mmd^{-1} (Table 2). Any conclusion drawn from this Coshocton analysis must remain uncertain. It does indicate that accuracy of ET_x equations fitted with the Coshocton data should be interpreted with caution.

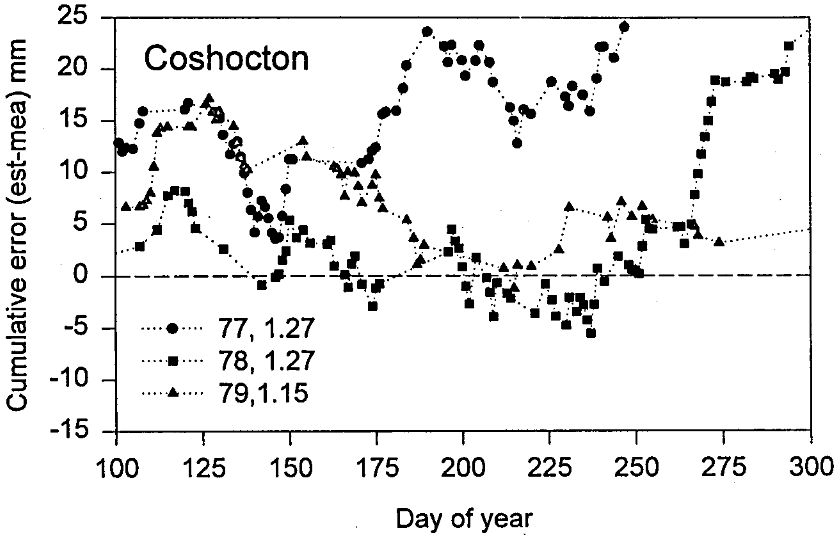

Figure 5. Cumulative annual differences between daily estimated minus measured evapotranspiration for grass at Coshocton (CO), OH with lysimeter corrections for three years using a fitted vapor pressure deficit (VPD) constant of 6.7 in a combination equation to minimize the errors.

CONCLUSIONS

Results from this study illustrate the weaknesses and strengths of using lysimeter data for developing and calibrating ET_x equations. Although there are several sources of errors in measurements and estimation of evapotranspiration with lysimeter data, we believe that biases caused by inaccurate calibration of solar radiation sensors, lysimeter rim area and representative plant exposure of lysimeters are the most likely major cause of biased estimates of ET_x equation parameters. When researchers are aware of these error possibilities, biases can be reduced although never eliminated. Lysimeters with large areas and small gaps, such as those at Bushland, are least likely to have bias problems when care is taken to make sure that the net leaf area overlapping the inside and outside of the lysimeter is near zero. We believe that lysimeter overlaps of up to ± 10% cannot be visibly detected for crops like wheat and alfalfa. The wheat data from Bushland in 1988, had likely biased errors of about 10% caused by lack of uniformity around the gap area. If the biases evaluated herein are correct, the errors in estimation of ET_x, would be less than ±5% when using the original data most of the time, except for Coshocton.

Researchers involved in future measurements of evapotranspiration for evaluating ET_x equations should consider those type problems and take the extra time and expense to minimize biases if the results are to be useful to those seeking to improve water use assessment.

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